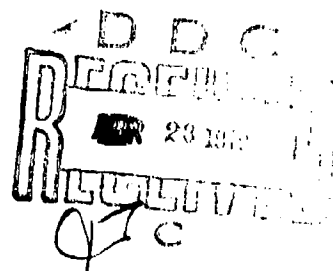LEVEL

AFAPL-TR-79-2014

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FUEL HYDROGEN CONTENT AS AN INDICATOR OF RADIATIVE HEAT TRANSFER
IN AN AIRCRAFT GAS TURBINE COMBUSTOR

Fuels Branch
Fuels and Lubrication Division

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February 1979
TECHNICAL REPORT AFAPL-TR-79-2014
Final Technical Report for the Period June to November 1976

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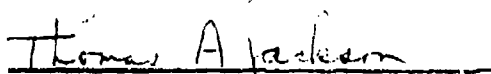WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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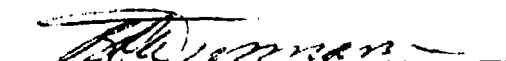

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FOR THE COMMANDER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Eleven fuels representing a wide range of hydrogen content were studied using a T56 single can combustor rig. Test fuels included single and double ring aromatic types as well as paraffins blended with each other and with JP-4. Fuel mixtures with hydrogen contents ranging from 9.9 to 15.9 per cent by weight were examined. The combustor inlet conditions simulated the discharge from both low and high pressure ratio gas turbine compressors operating at the cruise condition. Thermocouple data from the T56 liner are correlated with fuel hydrogen content using a new, nondimensional combustor liner

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temperature parameter. Least-squares mathematical treatment of the data resulted in an excellent second order correlation between the nondimensional temperature parameter and fuel hydrogen content and a simplified radiation analysis is presented which also explains the resulting empirical trends.

FOREWARD

This report describes an in-house effort conducted by personnel of
the Fuels Branch (SFF), Fuels and Lubrication Division (SF), Air Force
Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories,
Wright-Patterson Air Force Base, Ohio, under Project 3048, "Fuels,
Lubrication, and Fire Protection," Task 304805, "Aero Propulsion Fuels,"
Work Unit 30480590.

The work reported herein is an extension of the liner temperature/
fuel hydrogen content relationship reported in AFAPL-TR-77-93. This
report develops the theoretical foundation upon which the empirical
equation describing the above relationship is based. Specific data upon
which this report is based can be found in the Tabulations presented in the
Appendices of AFAPL-TR-77-93.

This material was originally submitted as a paper to the American
Society of Mechanical Engineers (ASME) for presentation at the Winter Annual
Meeting of the ASME held in Atlanta, Georgia, November 27 through
December 2, 1977. The paper was presented by Mr. T. A. Jackson.

Dr. W. S. Blazowski was employed at the Air Force Aero Propulsion
Laboratory during the test program upon which this paper is based. He
then collaborated with Mr. Jackson in writing the paper after beginning
his employment with Exxon Research and Engineering Company.

ACKNOWLEDGEMENTS

iii

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1   SUMMARY

This report represents an extension of work performed in the in-house combustion facility at the Air Force Aero Propulsion Laboratory in the area of alternate fuel investigations. The thrust of the in-house alternate fuel area has been to evaluate the sensitivity of standard combustor configurations to variations of selected fuel properties.

The fuel hydrogen content has been identified as the property with potentially the most influence on combustion hardware durability. Vast amounts of testing have indicated that, in systems typified by fuel rich primary flame zones, reduced fuel hydrogen content has a significant impact on increasing combustion liner surface temperatures. It is postulated that the hydrogen deficient fuel causes an increase in the soot formation tendency of the combustor's primary flame zone (particularly in the fuel rich systems). This increase in soot production increases the emissivity of the primary zone and results in more efficient transfer of heat to the combustor liner. This manifests itself as increased liner temperatures.

This report presents work accomplished with a T56 single can combustor (representative of the class described above) and eleven test fuel blends of different hydrocarbons. The intent of the investigation is to specifically examine the relationship between fuel hydrogen content and the combustor liner temperature. As a result, fuels with a wide range of hydrogen content are utilized (the range is actually larger than would ever be anticipated in production jet fuel), and the hydrogen content is achieved by the use of different hydrocarbon compounds to reduce the possibility that the results are hydrocarbon type dependent. A second order correlation of the data is compared to an equation resulting from a simplified radiation analysis of the combustor's primary flame zone. The agreement is excellent.

2   INTRODUCTION

Between 1973 and 1976, the cost and availability of aircraft jet fuels have drastically changed. Per-gallon jet fuel costs have more than tripled for both commercial and military consumers. In addition, fuel procurement actions have encountered difficulties in obtaining desired quantities of fuel, even though significantly reduced from 1972 consumption levels. These developments have encouraged initial examinations of the feasibility of producing jet fuels from nonpetroleum resources (1-4)[1].

Although economics and supply are primarily responsible for this recent interest in new fuel sources, projections of available world-wide petroleum resources also indicate the necessity for seeking new means of obtaining jet fuel. Regardless of current problems, the dependence on petroleum as the primary source of jet fuel can be expected to cease sometime within the next half century (4-5).

If the general nature of future aircraft (size, weight, flight speed, etc.) is to remain similar to today's designs, liquid hydrocarbons can be

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[1]Underlined numbers in parentheses designate
References at end of report

1

expected to continue as the primary propulsion fuel. Liquefied hydrogen and methane have been extensively studied as alternatives but seem to be practical only for very large aircraft. The basic nonpetroleum resources from which future liquid hydrocarbon synfuels might be produced are numerous. They range from the more familiar energy sources of coal, oil shale, and tar sands to possible future organic materials derived from energy farming. Experience to date indicates that basic synthetic crudes, especially those produced from coal, will be appreciably different than petroleum crude. Most importantly, reduced fuel hydrogen content would be anticipated in jet fuels produced from these alternate sources.

Because of the global nature of aircraft operations, jet fuels of the future are likely to be produced from a combination of these basic sources. Production of fuels from blends of synthetic crudes and natural crudes may be expected. In light of the wide variations in materials from which world-wide jet fuel production can draw, it is anticipated that economics will dictate the acceptance of future fuels with properties other than those of currently used JP-4, JP-5, and Jet A.[2] Much additional technical information will be required to identify the fuel characteristics which provide the optimum solution to the following objectives:

a) allow usage of key world-wide resources to assure availability

b) minimize the total cost of aircraft system operation

c) avoid sacrifice of engine performance, flight safety, or environmental impact

A complex program is necessary to establish the information base from which future fuel specifications can be made. This overall program must be integrated by a system optimization study intended to identify the best solution to the stated objectives. One of the most important inputs to an optimization study will be any effect of future fuels on the life of engine component hardware, especially that of the combustor. This report addresses the nature of the fuel property that is believed to most strongly impact the life of the gas turbine combustor, the fuel hydrogen content.

3   BACKGROUND

Fuel hydrogen content is the most important parameter anticipated to change significantly with the use of alternate fuels. In particular, fuels produced from coal or oil shale would be expected to have significantly reduced hydrogen content. In most cases, reduction in fuel hydrogen content would be due to increased concentrations of aromatic-type hydrocarbons in the fuel. These may be either single ring or polycyclic in structure.

Experience has shown that decreased hydrogen content significantly influences the fuel pyrolysis process in a manner which results in increased rates of carbon particle formation. For example, Wright (6) has demonstrated

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[2] JP-4 and JP-5 are designations of the standard Air Force and Navy aircraft gas turbine engine fuels, respectively. Jet A is the designation of the standard, high freeze point commercial aviation gas turbine engine fuel.

2

that the equivalence ratio for incipient soot formation in a well-stirred reactor is a strong function of fuel hydrogen content. These particulates are responsible for the formation of a luminous flame within the combustor. It is theorized that radiation from these particles becomes the predominant mode of heat transfer. The increased radiative loading on combustor liners which results from decreased hydrogen content can be substantial. Increases exceeding 100°K have been reported (7, 8). These variations in liner temperature can translate into serious decreases in hardware life and reliability.

A substantial amount of work has been done at the Air Force Aero Propulsion Laboratory (AFAPL) using a T56[3] single combustor which verified the strong influence of fuel hydrogen content on the temperature of the combustor liner (7, 8). Primarily the work has been conducted using JP-4 or JP-5 blended with xylene (an aromatic hydrocarbon) in various quantities to produce test fuels with hydrogen content ranging from 12 percent by weight to the current JP-4 value of 14.5.

This report discusses additional work intended to expand the scope of previous investigations in three respects. Firstly, the range of fuel hydrogen content investigated was expanded to 9.9-15.9 weight percent. This was done in order to better correlate the effect of hydrogen content on liner temperature and to explain the physical phenomena responsible, presumably radiation heat transfer from the luminous primary flame zone. Secondly, this work sought to determine whether the combustor liner temperature/fuel hydrogen content correlation is a function of the molecular structure of the hydrocarbon resulting in reduced fuel hydrogen content. A number of hydrocarbon types, in addition to xylene, have been investigated. Finally, the severe test conditions encountered using these lower hydrogen content fuels resulted in attrition of thermocouples during testing. Replacement of the combustor or reinstrumentation of the original combustor was necessary. Consequently, the data acquired have allowed an evaluation of the ability of the nondimensional temperature parameter (7, 8) to normalize combustor-to-combustor and thermocouple positioning variations.

4   EXPERIMENTAL

4.1   Facilities

All testing was performed in the AFAPL combustor rig facility. Air, supplied by a series of three Ingersol Rand compressors, is heated to temperatures simulating various conditions of compressor discharge by passing through an unvitiated, gas fired furnace. The system is capable of supplying 3.4 kg/sec of air at 18 atm pressure and temperatures up to 840°K. Accurate control of combustor air flow and pressure is accomplished by an automatic air bleed control valve and an exhaust plug operated from the control room. A 5-centimeter throat diameter venturi is used to measure air flow; fuel flow is determined using a turbine flow meter. All inlet and exhaust temperatures are measured with chromel alumel thermocouples.

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[3]The T56 is a turboprop gas turbine engine developed by Detroit Diesel Allison Division of General Motors Corporation.

3

T56 Series III single combustors were utilized in this study. Six combustors of the type tested (see Figure 1) are arranged in annular fashion in the T56 engine which is used in the C-130 aircraft. Although the T56 combustor has specific operating conditions of inlet temperature, air flow rate, fuel-air ratio, and pressure, the combustor was operated at conditions simulating two engine types (high and low pressure ratio) operating at subsonic cruise. Air flow at all conditions was scaled to simulate a constant compressor discharge Mach Number. In effect, this allows air mass flow to be scaled with static pressure and temperature as $PT^{-\frac{1}{2}}$. Considering facility limitations, T56 combustor design requirements, and the above described scaling law, the conditions listed in Table 1 were selected as the basis for the tests conducted.

Table 1 Combustor rig test conditions for simulations of low pressure ratio (L.P.) and high pressure ratio (H.P.) cruise operation

| Parameter	Condition	
	L.P. Cruise	H.P. Cruise
Inlet Pressure (ATM)	7.8	8.5
Air Mass Flow (kg/sec)	2.00	2.04
Inlet Temperature (^{o}K)	644	756
Exit Temperature (^{o}K)*	1200	1200

* Based on 100% combustion efficiency

The combustor liner was instrumented with sixteen chromel-alumel thermocouples in the arrangement shown in Figure 1. These direct measurements provided the only means of determining the effects of increased combustion zone radiation (actual radiation measurements were not accomplished). Analysis of the exhaust smoke was attempted. However, the excessive smoke emission from some of the initial test fuels (notably pure xylene) overloaded the instrumentation and rendered it temporarily inoperable. The decision was made to continue the testing without smoke measurements. In addition, gaseous emissions were not determined. Previous experience indicated that combustion efficiency at cruise conditions was always greater than 99 percent at the test conditions listed in Table 1 and that gaseous exhaust emissions were not significantly affected by hydrogen content ([8]).

4.2 Test Fuels

Test fuels were not extensively analyzed for this investigation, as all components (other than JP-4) were pure hydrocarbons. The JP-4 used in this investigation as a blending component was extensively analyzed for previous testing (Fuel AFFB-73-16, References [7], [8]). Its properties are repeated here in Table 2. The test fuels were blended to predetermined hydrogen contents by calculating the mass fraction required of each component based on the component's weight percent of hydrogen. After blending nearly all test fuels were analyzed for their final hydrogen content utilizing a CHN Elemental Analyzer, [4] manufactured by CARLO ERBA of Italy. The results of this analysis verified the accuracy of the fuel hydrogen contents calculated from the known blending mass fractions.

[4] This analyzes for weight percentages of Carbon, Hydrogen, and Nitrogen.

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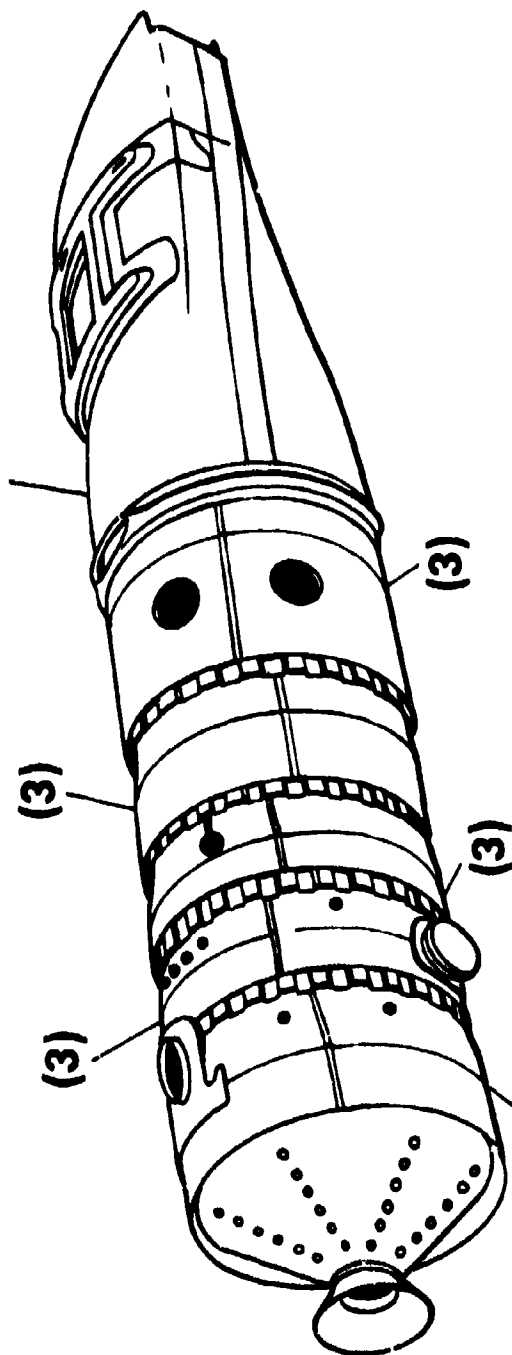
THERMOCOUPLES
120° APART

FIGURE 1 T56 Series Three Combustor

5

Table 2 Analysis of JP-4 used in blending.

Property	JP-4 AFFD-73-16
Aromatics (Volume %)	9.4
Olefins (Volume %)	1.2
Sulfur Mercaptan (Weight %)	0.000
Sulfur Total (Weight %)	0.030
Distillation	
Initial Boiling Point ($^{\circ}$K)	334
10% Rec ($^{\circ}$K)	372
20% Rec ($^{\circ}$K)	383
50% Rec ($^{\circ}$K)	417
90% Rec ($^{\circ}$K)	497
Final Boiling Point ($^{\circ}$K)	520
Gravity API	56.0
Vapor Pressure (atm)	0.156
Freeze Point ($^{\circ}$K)	B 216
Aniline Gravity Product	7903.
Heating Value Calculated (Cal/gm)	10,451
Carbon (Weight %)	85.14
Hydrogen (Weight %)	14.49
Nitrogen (Weight %)	0.003
Oxygen (Weight %)	0.11

The test fuels and their corresponding hydrogen weight percentages are tabulated in Table 3. For this investigation, xylene was used pure as a test fuel (Fuel B) and in blends with JP-4 (Fuels C, D, H, and J). Xylene represents a single ring aromatic hydrocarbon. Iso-octane (2-2-4 trimethyl-pentane) was used pure as a test fuel (Fuel F) and in blends with JP-4 (Fuel E) and with Decalin, decahydronaphthalene (Fuel K). Iso-octane represents a parafin. Decalin represents a fully saturated double ring hydro-carbon. Naphthalene, solid at room temperature, was used in solution with xylene (on a 1 to 1 by weight basis) and this solution was then blended with JP-4 (Fuel G). Naphthalene represents a completely unsaturated double ring hydrocarbon. Finally, Tetralin (tetrahydronaphthalene) was used in solution with JP-4 (Fuel I). Tetralin represents a double ring hydrocarbon, half of which is saturated while the other ring is fully aromatic.

Table 3 Test fuel/test series summary.

Fuel	Composition	Weight % Hydrogen	Test Series
A	JP4	14.5	I, II, III, IV
B	Xylene	9.9	I
C	JP4/Xylene	10.5	I
D	JP4/Xylene	11.5	I, III, IV
E	JP4/ Iso-Octane	15.2	II
F	Iso-Octane	15.9	II
G	JP4/Naphthalene/Xylene	12.5	II
H	JP4/Xylene	12.5	III, IV
I	JP4/Tetralin	12.5	III, IV
J	JP4/Xylene	13.5	III, IV
K	Iso-Octane/Decalin	14.5	II

6

4.3   Test Plan

Fuels B, C, and D were studied to extend the range of hydrogen content previously investigated. Two additional fuels (fuels H and J) were tested to examine the reproducibility of results attained in previous testing on this system (Reference 7, Phase I). To examine the combustor liner temperature correlation for hydrogen contents greater than that of JP-4, fuels E and F were tested. Evaluation of the effect of hydrocarbon type (molecular structure) used in blending was accomplished by testing fuels G, I, and K.

The testing was conducted in four series extending from August 1976 thru October 1976. Within each series both cruise conditions (Table 1) were tested. The fuels involved in each series are indicated in Table 3. As noted, some fuels were involved in more than one series. Series I and II were conducted on the same T56 single combustor, and without any instrumentation change. Series III was conducted with a second T56 can, newly instrumented, with a slightly richer primary zone than the can initially used. Series IV was conducted with the original T56 can, fully reinstrumented. The test fuels used in Series IV were identical to those used in Series III to determine any effects of the differences in combustor cans.

In each series and between each set of test fuel data points (fuels were examined up to four times at each condition; thus, up to eight times within a series) the combustor was operated with a typical JP-4 to assure repeatability and proper operation of all measurement equipment. The JP-4 used as the baseline was from a facility source, not the same as that used as a blending stock. However, the blending JP-4 (Fuel AFFB-73-16) was tested against the facility JP-4 and identical results were obtained in all respects. Therefore, the facility JP-4 data was considered to be baseline fuel information.

5   RESULTS

The more luminous flame produced as fuel hydrogen content is decreased was found to substantially increase combustor liner temperature at both cruise conditions studied. Each incremental decrease in fuel hydrogen content results in a significant combustor liner temperature increase. Since two T56 cans were used in this investigation and since one of these cans was instrumented twice, a nondimensional temperature parameter was used to compare liner temperature, from one can to another and from one fuel to another. The following nondimensional temperature parameter was developed from earlier work performed at AFAPL ([7], [8]):

$$T.P. = \frac{T_L - T_{LO}}{T_{LO} - T_3} \qquad (1)$$

The numerator of this expression represents the increase in combustor liner temperature, T_L, over that obtained using the baseline fuel (14.5% hydrogen JP-4), T_{LO}. This is normalized by the difference between T_{LO} and combustor inlet temperature, T_3. Thus, the parameter is representative of the fractional increase (over the baseline fuel) in heat transfer to the combustor liner. Values for T_L and T_{LO} are determined from the maximum number of thermocouples intact in the area of interest on the liner throughout the testing of an entire condition. Since thermocouples were lost as the testing progressed, the data base for T_L and T_{LO} changed periodically.

7

5.1   Evaluation of Nondimensional Parameter

In conducting tests to measure reduced fuel hydrogen effects
on the combustor liner temperature, the second, third, and fourth panels
of the T56 liner have traditionally been averaged and this average has then
been used as T_L in the temperature parameter ([7], [8]). These three panels
have been used since they are essentially closest to the primary flame
zone of the T56 and as such would be most sensitive to any luminosity
changes in the flame zone. In this present investigation the pure xylene
(the lowest hydrogen content fuel studied) tested in the first series
stressed the liner thermocouples to the extent of damaging all the thermo-
couples on the third panel (center panel of the three normally averaged).
As a result, only two panels could be averaged in formulating T_L for each
test fuel in Series I and II. For consistency T_L for fuels in Series III
and IV was also formulated from the information of only two panels.

The fully instrumented cans used in Series III and IV present
an opportunity to evaluate the acceptability of using two panels instead
of three to calculate the temperature parameter. In Tables 4 and 5 the
parameter is presented for all conditions tested based both on the average
temperatures obtained considering two panels as well as considering three
panels. The result of the comparison indicates that basing the parameter
on only two panels is fully acceptable.

The nondimensional temperature parameter has been utilized in
the data analysis because it permits comparison of data between different
combustors (or the same combustor reinstrumented) and between combustors
operated at different conditions. A comparison of the data in Tables 4
and 5, as well as the plot in Figure 2, indicates the validity of these
presumptions. The values of the parameter for Test Series III and Test
Series IV (representing two different T56 cans) compare very well with each
other, even from one condition to another. The only significant discrepancy
in the results involves the low inlet temperature condition series of Table
5. The values of the parameter for fuels H, and J appear somewhat high
compared to the other condition and compared to Test Series III. A good
reason for this discrepancy could not be found after reviewing the raw
data so eliminating the results of this set of data from the analysis could
not be justified. It should be noted, however, that this set of data was
the last taken in this investigation (it was run after the higher inlet
temperature series). This test was different in one potentially signifi-
cant aspect; the digital flow meter (reading out in gallons per hour) was
not operating during the last series. As a result, a less accurate flow
measurement device was used to measure the fuel flow rate (measured in
percent of a zero to eighty gallon per hour scale). The net result on the
test conditions was that the exhaust gas temperature was consistently
about $10°$K higher than in preceding tests.

With the above mentioned exception involving fuels H and J,
Tables 4 and 5 illustrate the similarity between the two cruise conditions
(inlet temperatures of 644 and $756°$K). This has allowed correlation to be
established for all data without discriminating between the two cruise
conditions.

8

Table 4 Test Series III, nondimensional temperature parameter (T.P.)

L.P. Cruise/T3 = 644°K

Fuel	Weight % Hydrogen	T.P. Based on 2 Panels	T.P. Based on 3 Panels
D	11.5	0.28	0.28
H	12.5	0.19	0.19
I	12.5	0.23	0.23
J	13.5	0.10	0.10

H.P. Cruise/T3 = 756°K

D	11.5	0.29	0.29
H	12.5	0.20	0.21
I	12.5	0.21	0.21
J	13.5	0.10	0.11

Table 5 Test Series IV, nondimensional temperature parameter (T.P.)

L.P. Cruise/T3 = 644°K

Fuel	Weight % Hydrogen	T.P. Based on 2 Panels	T.P. Based on 3 Panels
D	11.5	0.29	0.30
H	12.5	0.27	0.27
I	12.5	0.25	0.26
J	13.5	0.15	0.15

H.P. Cruise/T3 = 756°K

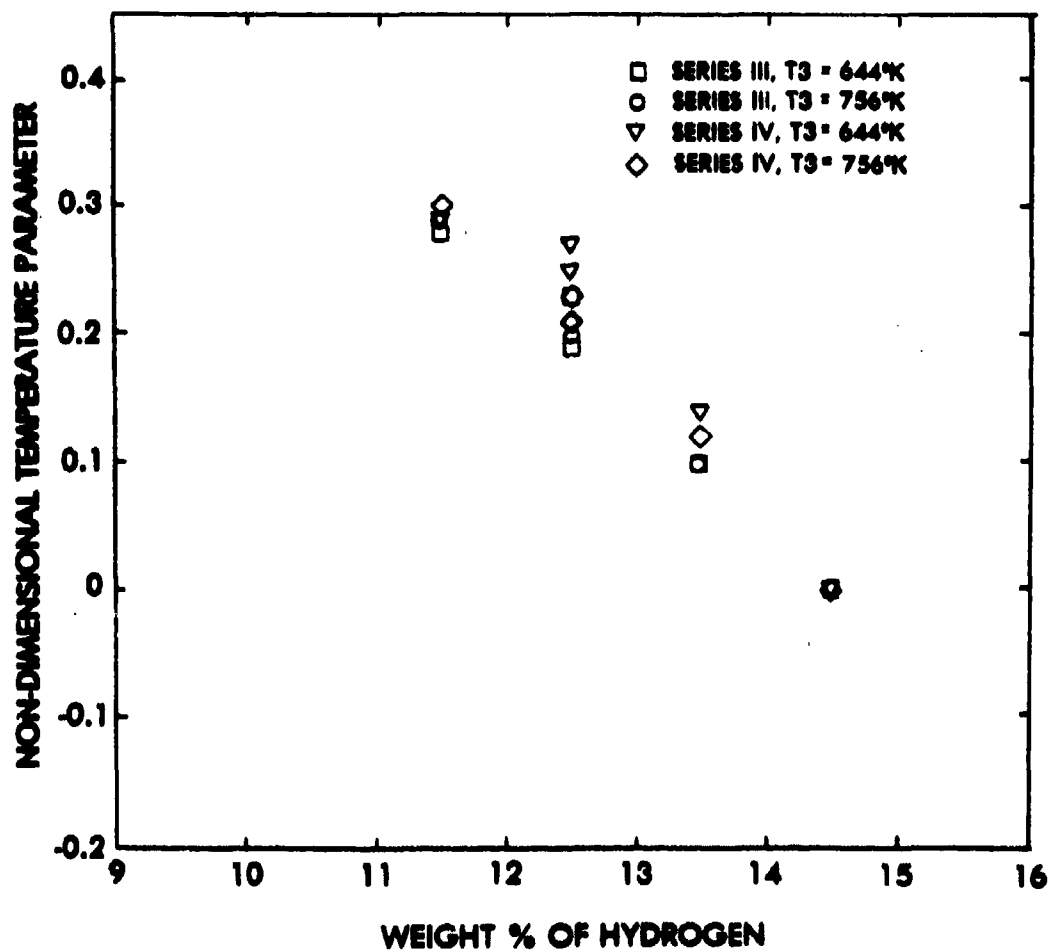| D | 11.5 | 0.30 | 0.30 |
H	12.5	0.21	0.21
I	12.5	0.23	0.23
J	13.5	0.12	0.12

FIGURE 2. Illustration of Data Repeatability

5.2 Expanded Range of Hydrogen Content

Information relating to the expanded range of fuel hydrogen content includes results from testing of fuels B thru F, and fuels H and J as well as three fuels tested in a previous investigation at AFAPL ([7], [8]). In previous testing, thermocouple data from the mid-three combustor liner panels were used to determine the temperature parameter. During Series I of this investigation, however, the thermocouples on the center panel failed and thus were not used to calculate the nondimensional temperature parameter. Only the measured temperatures of the outer two panels could be averaged. The validity of this step was discussed in Section 5.1. The subject results have been plotted in Figure 3 along with the correlation established in preliminary testing with the JP-4/xylene blends ([7], [8]). The new data are in agreement with the previous results indicating good reproducibility.

The overall correlation acquired using all data has been fit by least squared analysis to an equation of the form:

$$T.P. = C_0 + C_1 \cdot (H) + C_2 \cdot (H)^2 \tag{2}$$

where: T.P. = nondimensional temperature parameter

H = weight percent of hydrogen

C_0, C_1, C_2 = constants

The coefficients have been determined from the data for all JP-4/xylene blends (including those of Reference 7) and the JP-4/iso-octane blends. The resulting equation:

$$T.P. = -.098 + .138H - .009H^2 \tag{3}$$

has been plotted in Figure 4 with all the contributing data. The correlation is excellent.

It is of interest to attempt explanation of these results through consideration of the fundamental phenomena responsible for increased primary zone flame radiation. Calculations of adiabatic flame temperature for the fuel variations encountered here indicate that the changes in primary zone radiation are not due to increased temperature but must be associated with increased flame emissivity. Further, since the non-luminous infrared band emission (primarily CO_2)[5] does not vary widely with fuel type, emissivity increases can be attributed predominantly to the increased carbon particulate (soot) concentrations--that is, the luminous emissivity. The development of the appropriate mathematic correlation form implied by the association of soot concentration to increased combustor liner temperature follows.

A Beer's law analysis of combustion zone absorptivity (or emissivity) resulting from carbon particulates indicates:

$$\epsilon_c = 1 - e^{-KPc} \tag{4}$$

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[5] Abbreviation of Carbon Dioxide, a primary exhaust gas product from hydrocarbon and air combustion.
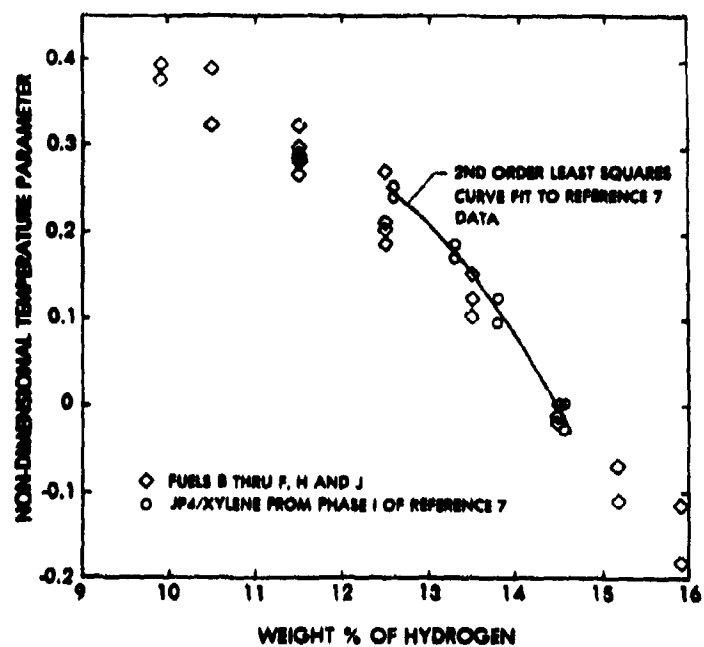
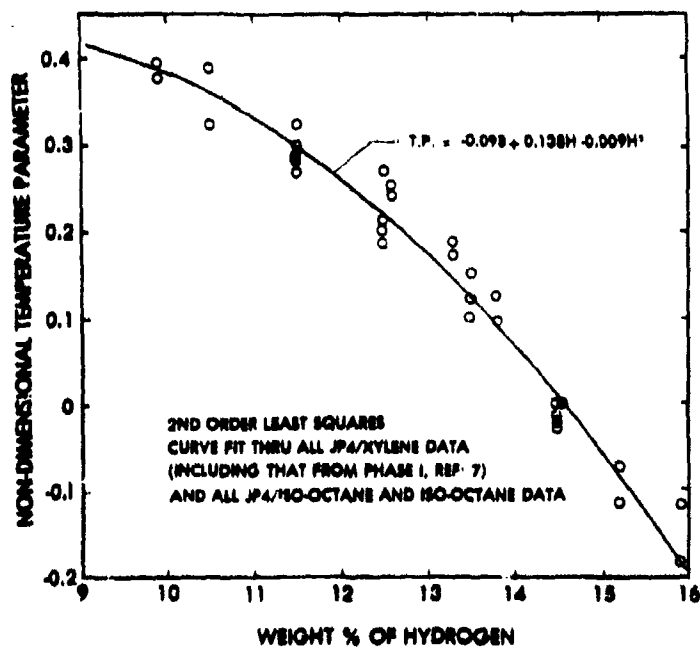FIGURE 3. Comparison of New Data with Previous Correlation

FIGURE 4. Overall Correlation between Hydrogen Content and
the Non-dimensional Temperature Parameter

12

where: ε_c = emissivity due to carbon particulates

K = absorption coefficient

P_c = carbon particle or soot concentration

For the low pressure, low equivalence ratio system discussed here, it will be assumed that the gas infrared band emissivity, ε_g is small (0.2) and that the ε_c and ε_g are additive. Further, it is assumed that ε_g variations with fuel type are insignificant compared with ε_c variations.

Equation 4 can be modified to allow fuel hydrogen content to be the independent variable. The following relationship between primary zone carbon particle concentration and hydrogen content is assumed:

$$\frac{P_c}{(P_c)_o} = 1 + C_3 (H_o - H)^n \tag{5}$$

where the subscript "o" refers to the JP-4 baseline fuel value, C_3 is a constant, and n corresponds to a global power law dependence of particulate concentration on hydrogen content. Equation 4 then becomes:

$$\varepsilon_c = 1 - e^{-K(P_c)_o(1 + C_3\Delta H^n)} \tag{6}$$

where: $\Delta H = H_o - H$.

Since the temperature parameter, TP, can be considered to be a ratio of increase in the primary zone radiation with a test fuel to that using the baseline fuel, and since the emissivity is the parameter primarily responsible for radiation variation:

$$TP = \frac{(\varepsilon_c + \varepsilon_g) - (\varepsilon_c + \varepsilon_g)_o}{(\varepsilon_c + \varepsilon_g)_o} = \frac{\varepsilon_c - (\varepsilon_c)_o}{(\varepsilon_c + \varepsilon_g)_o} \tag{7}$$

$$TP = \frac{1 - e^{-K(P_c)_o(1 + C_3\Delta H^n)} - [1 - e^{-K(P_c)_o}]}{(\varepsilon_c + \varepsilon_g)_o} \tag{8}$$

$$TP = \frac{e^{-K(P_c)_o} [1 - e^{-K(P_c)_oC_3\Delta H^n}]}{(\varepsilon_c + \varepsilon_g)_o} \tag{9}$$

Now allowing the following simplifications:

$$C_4 = \frac{e^{-K(P_c)_o}}{(\varepsilon_c + \varepsilon_g)_o} \quad ; \quad C_5 = K(P_c)_oC_3$$

the result is $TP = C_4(1 - e^{-C_5\Delta H^n})$ \hfill (10)

13

Values for C_4 and C_5 can be calculated for different assumed n values. This was attempted for n = 1/2, 1, and 2 with the following results:

n	C_4	C_5
1	0.572	0.245
2	0.394	0.175
1/2	Solution not possible	

Table 6 compares the results of Equation 10 using these C_4 and C_5 values with the second order least squares correlation, Equation 3. The result for n = 1 provides excellent agreement and is considered to offer a more meaningful correlation form which can be used in conjunction with the nondimensional temperature parameter. It would be of interest in future fundamental, well-stirred reactor experiments (e.g., Reference 6) to examine the validity and further utility of Equation 5 as used in this simplified model.

Table 6 Comparison of simplified model with second order correlation

Hydrogen Content	n = 1/2	n = 1	n = 2	Equation 3
10		0.382	0.382	0.382
11		0.329	0.3478	0.331
12	Solution	0.262	0.262	0.262
13	Not	0.176	0.128	0.175
14	Possible	0.0659	0.0169	0.07
14.5		0.0	0.0	0.01

5.3   Effect of Hydrocarbon Type

The results of testing fuels of lower hydrogen content obtained in a manner other than blending the single-ring aromatic xylene with JP-4 can be used to examine the universality of the correlation discussed above. Fuels G, I, and K contain varying amounts of double ring hydrocarbon types as blending agents. Each of these fuels contains double ring "aromatic" compounds. G contains naphthalene, a completely unsaturated double ring compound. I contains a partially saturated double ring compound, Tetralin. K contains a double ring completely saturated compound, Decalin. Figure 5 compares the non-dimensional temperature parameter for each of these fuels with the correlation previously discussed. In each case, the results conform reasonably well to the correlation and it must be concluded that hydrogen content is the dominant factor determining fuel effects on combustion system hardware.

6   Summary and Conclusions

A primary difficulty in evaluating the response of combustion liner temperature to changing fuel properties involves data interpretation when more than one combustor or thermocouple orientation scheme is employed. In addition, liner temperature information obtained with various combustor
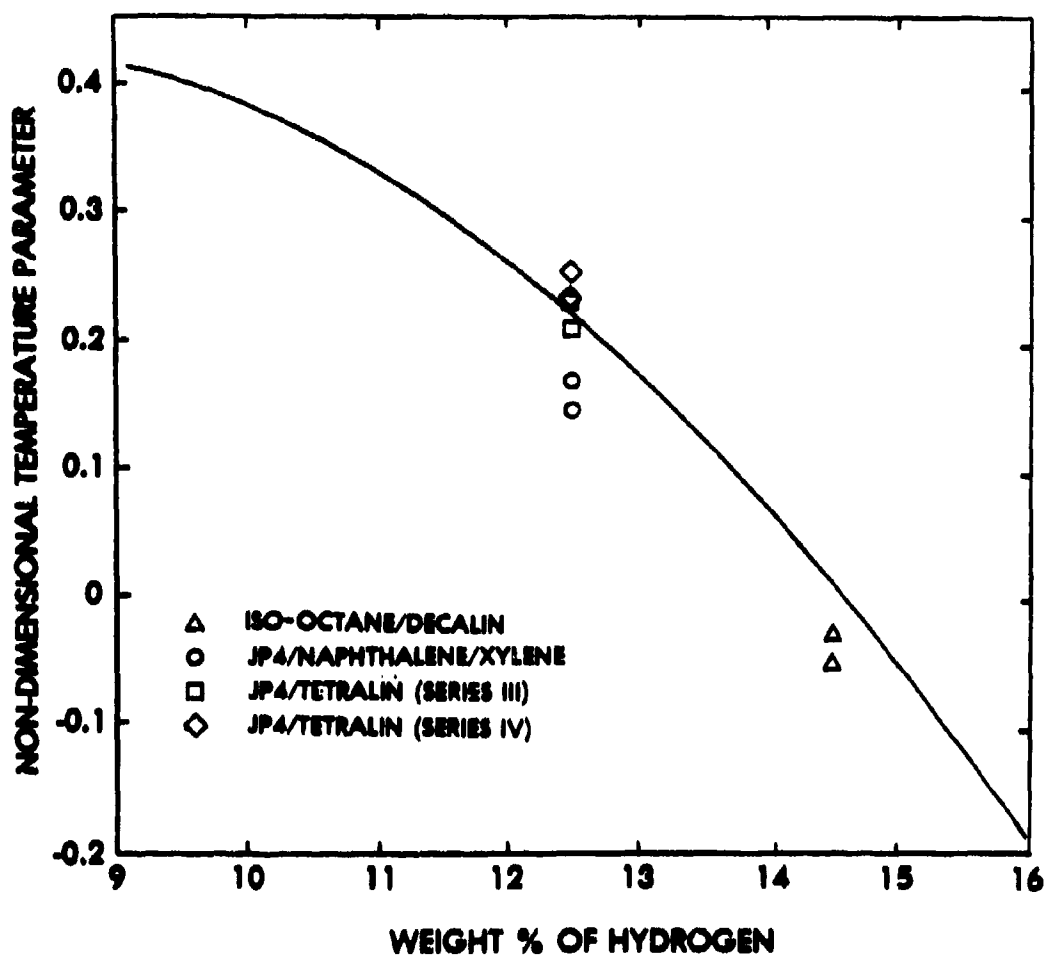
14

FIGURE 5. Effect of Blended Hydrocarbon Type on Correlation

15

designs (different engines) or at different combustor operating conditions
(combustor inlet temperature, fuel-air ratio, etc.) cannot be directly
compared because normal combustor operating conditions (the baseline) are
quite different for each design and operating mode. The nondimensional
temperature parameter previously developed to cope with these difficulties
(7, 8) has been shown to successfully normalize these effects from three
standpoints. First, it has been shown that thermocouple data from an
entire combustor liner panel could be eliminated without significantly
influencing correlations. Secondly, testing of different or newly
instrumented combustors has resulted in agreement with previous data.
The discrepancy with fuels H and J mentioned in Section 5.1 is considered
to be due to an error in fuel flow measurement or a procedural difficulty.
Finally, the sensitivity of the parameter to a change in the cruise
condition (inlet temperature change from 644 to 756 K) was such that all
cruise data could be analyzed together.

Data obtained by examining a wide range of fuel hydrogen
content (9.9 - 15.9% by weight) resulted in an excellent second order
correlation between fuel hydrogen content and combustor liner temperature.
This result is consistent with a simplified radiation heat transfer
model that assumes the dominance of luminous radiation and a power law
relationship between hydrogen content and primary zone particulate
concentration.

A variety of hydrocarbons were used as blending agents in
modifying the test fuel hydrogen content. These included xylene, iso-
octane, naphthalene, Decalin, and Tetralin. The test results indicate that
despite the hydrocarbon structure of the fuel blending component,
combustor liner temperature varies primarily with hydrogen content.

16

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